Potentiality of botanical agents for the management of post harvest insects of maize: a review

P. Lakshmi Soujanya¹ · J. C. Sekhar¹ · P. Kumar² · N. Sunil¹ · Ch. Vara Prasad³ · U. V. Mallavadhani³

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Abstract Natural products derived from plants are emerging as potent biorational alternatives to synthetic insecticides for the integrated management of post harvest insects of maize. In this paper, effectiveness of botanicals including plant extracts, essential oils, their isolated pure compounds, plant based nano formulations and their mode of action against storage insects have been reviewed with special reference to maize. Plant based insecticides found to be the most promising means of controlling storage insects of maize in an eco friendly and sustainable manner. This article also throws light on the commercialization of botanicals, their limitations, challenges and future trends of storage insect management.

Keywords Botanicals · Natural products · Nano based formulations · Maize · Plant extracts · Storage insects

Introduction

Maize is regarded as queen of cereal crops as it has highest genetic yield potential which is used as food, feed, fodder and also serves as basic raw material in industries such as beverage, confectionery, starch, ethanol, oil, cosmetic, pharma, food processing, textile, gum and paper industries. In India, Maize is a dominant crop with production of 24.19 million tones, exported 2.7 million tones grain worth Rs 4,267 crores to West Asia (DMR 2014); contributing 36 % in global grain production. It is rich in carbohydrate, protein, oil and crude fibre contents (FAOSTAT 2014). Though production of maize has increased to meet the global demand, several biotic and abiotic factors play an important role in limiting the productivity. It is also plagued with post production storage losses. Among biotic factors contributing for storage losses, insect pests play a major role inflicting 20–30 % damage of maize grain in tropical regions (Haque et al. 2000) due to favourable conditions for their development and poor storage conditions. It has been reported that more than 37 species of arthropod insects are associated with stored maize (Abraham 1997). Rice weevil *Sitophilus oryzae* L., (Coleoptera: Curculionidae), Angoumois grain moth *Sitotroga cerealella* (Oliv.) (Lepidoptera: Geleciidae), Red Flour beetle *Tribolium castaneum* (Herbst.) (Coleoptera: Tenebrionidae) lesser grain borer *Rhizopertha dominica* (F.) (Coleoptera: Bostrichidae) and Rice moth *Corcyra cephalonica* Stainton (Lepidoptera: Pyralidae) are the pests that attack maize in India. Among them, *S. oryzae* (Lucas and Riudavets 2000) and *S. cerealella* are the major primary insect pests causing quantitative and qualitative losses (Lakshmi Soujanya et al. 2013a); starts infestation in the field itself and continues in stored maize.

✉ P. Lakshmi Soujanya
soujanyak.scientist@gmail.com

J. C. Sekhar
jcswnr@rediffmail.com

P. Kumar
pradyumn.kumar@gmail.com

N. Sunil
sunilneelam9@gmail.com

Ch. Vara Prasad
Prasad.4096@gmail.com

U. V. Mallavadhani
mallavadhani@iict.res.in

¹ Winter Nursery Centre, ICAR- Indian Institute of Maize Research, Rajendranagar, Hyderabad 500030, India

² ICAR- Indian Institute of Maize Research, Pusa Campus, New Delhi 110 012, India

³ Natural Products Chemistry Division, CSIR-Indian Institute of Chemical Technology, Hyderabad 500007, India

They devour the seed completely from inside make them chaffy; and eventually seed viability is lost (Hill 2002). Infestation of these insect pests further result in mold formation (Magan et al. 2003); development of *Aspergillus*, (a fungus producing mycotoxins) which is the most powerful carcinogen in humans and animals (Williams et al. 2012, Carrieri et al. 2013) and phytotoxicity to grain (Lee et al. 2003).

Protection of stored products from insect pests is most important to ensure food supply to all over the world. Insect pests can be managed with the use of synthetic insecticides but in storage, any intervention with insecticides leads to closest application for consumption which is totally unsafe. Further, indiscriminate use of these synthetic insecticides resulted in the development of resistance (Subramanyam and Hagstrum 1995; Arthur 1996; Mohan et al. 2010; Correa et al. 2011), residues, undesirable effects on non target organisms, human and environmental hazards (White and Leesch 1995). Moreover, methyl bromide, one of the most effective fumigants in the control of stored pests, is banned from 2015 as per Montreal Protocol, due to its ozone depleting nature (Fields and White 2002; Philips and Throne 2010; Germinara et al. 2012). As a result, managing storage insects has become more of a challenge. In view of negative fallouts of synthetic insecticides, substances of plant origin for the control of stored grain insects are quite promising as they are more biodegradable, low toxicity to human beings; and there is every possibility of maintaining environmental conditions inside the storage systems (Guzzo et al. 2006).

Botanical insect toxins are extracted or derived from plants such as azadirachtin from *Azadirachta indica* A. Juss (Barceloux 2008), rotenone from *Derris elliptica* Wall. (Sae-Yun et al. 2006), pyrethrin from *Chrysanthemum cinerariifolium* Trevir. (Shawkat et al. 2011). The use of locally available plants including *Nicotiana*, *Ryania*; spices-turmeric, clove, cinnamon, black pepper, ginger, garlic, star anise for the control of insect pests is an ancient practice (Thacker 2002; Kiruba et al. 2008; Paul et al. 2009). Many of these plants are widely used in traditional medicine for treatment of various ailments also (Ahalya and Mikunthan 2013). Plants are the most efficient producers of secondary metabolites, that are used in defense against different insect pests (Isman and Akhtar 2007); particularly triterpenoids, iridoid glycosides which are responsible for insecticidal activities (Sharma 1995). Many researchers have worked on plant products as they provide unique mode of action (Koul and Dhaliwal 2001; Regnault- Roger et al. 2005; Santos et al. 2011) against storage insects due to their biodegradability, broad spectrum activity and sustainability.

Plants belonging to the families of Annonaceae, Asteraceae, Apiaceae, Chenopodiaceae, Cupressaceae, Lauraceae, Lamiaceae, Meliaceae, Myrtaceae, Poaceae, Piperaceae, Rutaceae, Verbenaceae and Zingiberaceae were reported as promising sources of botanical insecticides

(Isman 1995; Ukeh et al. 2010; Ebadollahi 2011; Suthisut et al. 2011; Rajashekar et al. 2014a) against storage insects. It is not necessary that all plant derivatives are non toxic, some are fast acting, potent carcinogens occur naturally such as nicotine (Park et al. 2003; Isman 2006; Rajendran and Sriranjini 2008; Regnault-Roger and Philogene 2008). In view of the above, a concise review is provided on plant derived pesticides with emphasis on plant extracts/ essential oils/ isolated compounds/ nano based formulations exhibiting insecticidal, repellent, antifeedant and fumigant activities against storage insects of maize and indicated some future directions to fill the gaps.

Effect of plant extracts and isolated pure compounds on storage pests of maize

Many previous attempts have been carried out on plant based derivatives against *S. oryzae*, *Sitophilus zeamais*, *T. castaneum* compared to *S. cerealella*, *R. dominica* and *C. cephalonica*. Plant powders, their extracts, isolated pure compounds were effective and considered eco friendly in storage insects control. Table 1 lists some of the plants tested for insecticidal activities against storage insects of maize. The bioactivity of plant extracts against storage insects of maize have been studied by numerous authors (Ogendo et al. 2004; Mihale et al. 2009; Sori 2014).

A. Bioactivity of plant extracts on adults

Sharma (1999) reported that neem seed, neem kernel powder at 4 % and neem leaf powder at 5 % concentration protected maize for 5 months against *S. oryzae*, *S. cerealella*, *R. dominica* and *T. castaneum*. Also many studies have shown the effectiveness of neem against storage insects of maize (Huang and Ho 1998; Mulungu et al. 2007; Sule et al. 2012; Chebet et al. 2013). Li et al. (2000) reported that isolated fraction from leaf of *Eupatorium adenophorum* Spreng. showed insecticidal activity against *S. oryzae* (LD₅₀-15.5 mg/L). Jayasekara et al. (2005) reported that root powder of *Securidaca longepedunculata* Fers, its methanol extract and isolated compound methyl salicylate has repellent and toxic properties against *S. zeamais* adults. Additionally, fumigant effect was observed with 60 µl dose against *S. zeamais* and *R. dominica* and prolonged exposure of methylsalicylate for 6 days provided 100 % mortality of two insect pests. Saljoqi et al. (2006) observed promising results on repellency and toxicity against *S. oryzae* using ethanol extract of bakain fruits at 10 % concentration. According to Potenza et al. (2006), acetone extracts of *Dahlia pinnata* Cav., *Ruta graveolens* L. and *Dieffenbachia brasiliensis* Veiech at 5 % concentration gave 87.0, 80.0 and 75.0 % mortality for *S. zeamais* adults, respectively when tested for contact

Table 1 List of plants tested for insecticidal activities against storage insects of maize

Common Name	Scientific Name	Family Name	Plant part used	Phytochemical Constituents	Target pest	References
Sweet Flag	<i>Acorus calamus</i> L.	Acoraceae (Araceae)	Rhizome	Asarone, choline, eugenol, ethyl ether, heptanoic acid, methylamine, saponin, tannic acid and trimethylamine	<i>Strophilus oryzae</i> , <i>Tribolium castaneum</i>	Chander et al. (1990)
Goat Weed	<i>Ageratum conyzoides</i> L.	Asteraceae	Leaf and stem	α -pinene, eugenol, steroids, flavonols, glucosides and polyoxygenated flavones	<i>T. castaneum</i>	Jaya et al. (2014)
Dill	<i>Anethum graveolens</i> L.	Umbelliferae (Apiaceae)	seed	Carvone, d-limonene, phellandrene, Cis-dihydro carvone, P-cymene	<i>T. castaneum</i>	Chaubey (2007)
Kalmegh	<i>Andrographis paniculata</i> Burm.f.	Acanthaceae	Leaf	Andrographolide, phenols, tannins, alkaloids, anthraquinones and saponins	<i>S. oryzae</i>	Prakash et al. (1993)
Bullock's Heart	<i>Annona squamosa</i> L.	Annonaceae	Leaf and stem	Anonaine, corydine, isocorydine and aporphine	<i>S. oryzae</i>	Ashok kumar et al. (2010)
Mugwort	<i>Artemisia annua</i> L.	Asteraceae	Stem and Leaf	Cineole, tauremisin, sitosterol, tetracosanol, fernenol and thujone	<i>T. castaneum</i>	Tripathi et al. (2000)
Chinese Worm Wood	<i>A. capillaris</i>	Asteraceae	Stem and Leaf	1,8-cineole, germacrene and d-camphor	<i>Strophilus zeamais</i>	Liu et al. (2010)
Caraway	<i>Carum carvi</i> L.	Umbelliferae (Apiaceae)	Fruit	Carvone, sterols, triterpenes, myrcene, 1,8- cineole, unsaturated steroids, saponins, flavonoids, glycosides, pyrogallol, tannin and phloroglucinol	<i>S. zeamais T. castaneum</i>	Fang et al. (2010)
Indian Worm Seed	<i>Chenopodium ambrosioides</i> L.	Amaranthaceae	Fruit	Ascaridole, carene, cymene histamine, hydrocyanic acid, limonene, methyl salicylate, oxalic acid, saffrole, saponin and trimethyl amine	<i>S. zeamais</i>	Denloye et al. (2010)
Irula	<i>Cleome monophylla</i> L.	Capparidaceae	Whole plant	Epenolene, 1- α -terpeneol, pentacosane, humulene, phytol and 2-dodecanone	<i>S. zeamais</i>	Ndungu et al. (1995)
Red Water Tree	<i>Erythrophloeum suaveolens</i> Guill. & Perr.	Fabaceae	Bark	Cassidine, nor-cassidine, cassaine, cassamine, erythrophallamine, erythrophleine and homophleine	<i>S. zeamais</i>	Niber et al. (1992)
Blue Gum Tree	<i>Eucalyptus globulus</i> Labill.	Myrtaceae	Leaf	1,8-cineole and α pinene	<i>S. oryzae, T. castaneum</i>	Mishra et al. (2012)
Black Sesame	<i>Hyptis spiciagera</i> Lam.	Lamiaceae	Whole plant	Sesquiterpenes, sesquiterpene alcohol and menthol	<i>S. zeamais</i>	Wekesa et al. (2011)
Lavender	<i>Lavendula angustifolia</i> Mill.	Lamiaceae	Whole plant	Linalyl acetate, geranyl acetate, linalool, geraniol, limonene, d-pinene, coumarin, fufurool, d-borneol and cineol	<i>S. oryzae, R. dominica, T. castaneum</i>	Rozman et al. (2007)
Com Mint	<i>Mentha arvensis</i> L.	Lamiaceae	Leaf	Menthol, menthane and menthyl acetate	<i>S. oryzae T. castaneum</i>	Varma and Dubey (2001)
Pepper Mint	<i>Mentha piperita</i> L.	Lamiaceae	Leaf powder	Acetaldehyde, amyl alcohol, caproic acid, caprylic acid, carvacrol, carvone, cineole, ethyl alcohol, formic acid, fufural, isoamyl alcohol, isovaleraldehyde, isovaleric acid, limonene, linalool, menthol, methanol, methylamine, oxalic acid, phellandrene, pulegone, salicylic acid and valeric acid	<i>S. oryzae, T. castaneum</i>	Lashgari et al. (2013)
Horse Mint	<i>Mentha longifolia</i> L.	Lamiaceae	Leaf	Menthol, menthone, piperitone, piperitenone, linalool, carvone and eucalyptol	<i>T. castaneum</i>	Khani and Asghari (2012)
Bitter Gourd	<i>Momordica charantia</i> L.	Cucurbitaceae	Leaf and seed	Charantin, momordicin, foetidin, 5-hydroxytryptamine, diosgenin and p-sitosterol	<i>S. oryzae, T. castaneum</i>	UshaRani and Devamand (2011)
Sweet Basil	<i>Ocinum basilicum</i> L.	Lamiaceae	Leaf	Anethole, camphor, carvacrol, cineole, citral, esdragole, eugenol, linalool, saffrole, saponin and thymol	<i>S. oryzae, T. castaneum</i>	Mishra et al. (2012)
Guava	<i>Psidium guajava</i> L.	Myrtaceae	Leaf	Ineol, tannins, triterpenic acids, ursolic and oleanolic acids	<i>S. oryzae</i>	Akhtar et al. (2013)
Fenugreek	<i>Trigonella foenum-graecum</i> L.	Fabaceae	Leaf	Trigonelline, steroidal sapogenin and diosgenin	<i>S. oryzae, R. dominica</i>	Matter et al. (2008)
Garden Thyme	<i>Thymus vulgaris</i> L.	Lamiaceae	Leaf and flower	Thymol, caracrol, cymol, borneol, linalool and tannin	<i>R. dominica</i>	Mehrabadi et al. (2011)
Nirgundi	<i>Vitex negundo</i> L.	Verbenaceae	Leaf	β -caryophyllene, protocatechuic acid and oleanolic acid	<i>S. oryzae</i>	Rana et al. (2005)

activity. Huang et al. (2007) reported 100 % mortality of *R. dominica* at 48 h post-treatment with LD_{50} - 19.94 $\mu\text{g}/\text{cm}^2$ after 72 h treatment when treated with ethanol extracts of *Trigonella foenum-graecum* L. extract at 0.39 mg/cm^2 .

It has been reported that chloroform extract of *Aloysia polystachya* Griseb. at 10 mg/mL solution was found to be feeding deterrent while hexane extract of *Solanum argentinum* Bitter et Lillo at 0.31 mg/cm^2 strongly repelled adults of *S. oryzae*. (Adriana et al. 2008). The work of Othira et al. (2009) mentioned fumigant, repellent and feeding deterrence activity from hexane extract of *Hyptis spicigera* Lam. against *S. zeamais* and *T. castaneum* in stored maize. During the investigations on the toxic properties of combination of *Acorus calamus* L. rhizomes and *Thevetia neriifolia* Juss. seed extract, the lowest LC_{50} values (43.27 μgcm^{-1}) were found against *S. oryzae* at 24 h after treatment (Talukder and Khanam 2009). The contact application of methanolic root extracts of *Decalepis hamiltonii* Wight at 250 mg/kg seed showed significant toxicity against *S. oryzae*, *R. dominica* and *T. castaneum* (Rajashekar et al. 2010). Adeyemi et al. (2010) observed 50 % feeding deterrent activity of *T. castaneum* with 3,4,5,7, tetrahydroxy flavonol (quercetin-1) at 2 mg/ml isolated from chloroform extract of stem bark of *Bobgunnia madagascariensis* Desv. J.H. Kirkbr & Wiersema in stored maize; also Gressel and Ammann (2008) reported that quercetin (1) acts as an allelochemical as well as insecticidal to storage insects. Shayesteh and Ashouri (2010) observed complete mortality and reduced F1 progeny emergence of *R. dominica* with black pepper powder at 2.5 % concentration. Ishii et al. (2010) found repellent activity by using methanolic extract of *Cinnamomum* sp at 10 mg/ml against *S. zeamais*. Ethyl acetate eluted fractions of *Capsicum annuum* Linn., *Momordica charantia* L., *Solanum melongena* L. at 10 $\text{mg}/100$ mL showed 100 % mortality to *T. castaneum* and *S. oryzae* within 24 h of treatment in vapour form without affecting germination in stored maize (UshaRani and Devanand 2011). Plant powder of *Chenopodium ambrosioides* L. at a concentration of 5 g/kg seed and seed oil of *Pimpinella anisum* L. at a dose of 1.50 ml cm^{-2} caused 100 % mortality of *T. castaneum* after 14 days of exposure. Further, significant complete reduction of F1 progeny was achieved with the tested botanicals (Gomah and Sahar 2011).

Maximum mortality of 98.8 % was achieved to adult *S. zeamais* with neemazal at a concentration of 12 g/kg seed after 14 days of treatment and greatly reduced F1 progeny emergence (Nukeneine et al. 2011). Gandhi and Pillai (2011) mentioned the insecticidal activity and seed protective effect of leaf powders of *Punica granatum* L. and *Murraya koenigii* L. against *R. dominica*. Geng et al. (2011) reported that Jolkinolide B and 17 hydroxy Jolkinolide B isolated from ethanolic extracts of roots of *Euphorbia fischeriana* Steud. at concentration of 30 ppm possessed strong feeding deterrent activity against *S. zeamais* (EC_{50} = 342.1 and 543.9 ppm)

and *T. castaneum* (EC_{50} = 361.4 and 551.5 ppm). The crude leaf extracts and their chromatographic fractions eluted with ethyl acetate of *Cocos nucifera* L. and *Terminalia catappa* L. were found to be insecticidal and fumigants to adults of *S. oryzae* and *T. castaneum* (UshaRani et al. 2011).

Recent studies also proved the efficacy of plant extracts against storage insects. Thein et al. (2013) reported that crude extracts of *Citronella* at 20 % concentration had the strongest repellent effect on *Sitophilus* spp. Another plant extract from *Alpinia pyramidata* Blume at 7.5 % provided protection to maize grain by completely inhibiting the F1 progeny emergence. Ali and Mohammed (2013) found that methanol extracts of *Zingiber officinale* Roscoe caused 100 % mortality to *S. oryzae*. Jeon et al. (2013) studied contact and fumigant toxicity of chloroform fraction of methanolic extract of *Ruta chalepensis* L. and obtained 87.7 % mortality to *S. oryzae* at 1.02 mg/cm^2 . Further insecticidal constituents isolated from leaves of *R. chalepensis*, quinoline (2) (0.057 mg/cm^2), quinoline-4-carbaldehyde (3) (0.065 mg/cm^2) and quinoline-3-carbaldehyde (4) (0.092 mg/cm^2) were found to be most toxic to *S. oryzae*. Other studies have shown that *T. castaneum*, *S. oryzae* (up to 50 % after 24 h) and *R. dominica* (up to 60 % after 24 h) can also be repelled by plant extracts of *Anagallis arvensis* L., *Hibiscus rosa-sinensis* Linn. and *Lapsana communis* L. (Singh et al. 2013).

Pure compounds osajin (5), lupalbigenin (6), scandinone (7), sphaerobioside (8), genistein (9) and prenylated isoflavones (10) derived from *Derris scandens* Benth. caused 100 % toxicity to *T. castaneum* and *C. cephalonica* after 10th and 15th day of treatment, respectively (Usha Rani et al. 2013). Ashamo and Ogungbite (2014) reported that ethanolic extracts of seeds from *Aframomum melegueta* K. Schum, *Eugenia aromatica* (Baill.), *Piper guineense* Thonn et Schum and *Xylopi aethiopica* Dunal at 4 and 6 % concentration prevented the adult emergence of *S. cerealella*. Sagheer et al. (2014) reported that the acetone extract of *Trachyspermum ammi* L. at 10 % concentration showed notable repellent action against *T. castaneum*. Rajashekar and Shivanandappa (2014) reported contact toxicity of Decaleside II isolated from the edible roots of *D. hamiltonii* at 100 mg/kg grain against *S. oryzae* and *T. castaneum*. Sitosteryl- β -D-glucopyranoside (11) isolated from floral extracts of *Peltophorum pterocarpum* DC. Heyne at a dosage of 0.080 $\text{mg}/30$ g diet was found to be very potent in producing toxicity to adults of *S. oryzae* which might be due to easy penetration into insect cuticle (UshaRani et al. 2014). Rajashekar et al. (2014a) demonstrated contact and fumigant toxicity of methanolic extract from leaves of *Lantana camara* L. against *S. oryzae* (LC_{50} - 128 $\mu\text{l}/\text{l}$, LD_{50} - 0.158 mg/cm^2) and *T. castaneum* (LC_{50} - 178.7 $\mu\text{l}/\text{l}$, LD_{50} - 0.208 mg/cm^2). A recent study by Shah et al. (2015) indicated maximum repellency with aqueous plant extracts of *Mentha longifolia* L. followed by *Momordica charantia* L. (90.0 %), *Luffa*

aegyptiaca Mill. (80.0 %) at 25 % concentration against *Rhizopertha dominica*. The structures of the bioactive compounds isolated from plants tested against storage insects were shown in Table 2.

B. Bioactivity of plant extracts on immature stages

There have been relatively few reports in the literature concerning the control of immature stages of storage pests by the use of botanicals. It was reported that plant extracts inhibit the development of eggs and immature stages present inside the seed (Boeke et al. 2004). Acetone extract of *Ipomoea palmata* L. showed 57.8 % egg mortality of *C. cephalonica* at 100.0 % concentration (Dwivedi and Garg 2000). In other work, flower extracts of *L. camara* exhibited higher larval mortality, reduced fecundity and prolonged development period of *R. dominica* (Rao and Prakash 2002). Das et al. (2006) evaluated nimbecidine at 16 ml/kg seed against eggs of *T. castaneum* and observed inhibition of egg hatching, pupation and adult emergence. Rizk (2008) reported that ethanolic extract of *Melia azadirachta* L. at 0.1 µg/ larva caused 57.0 % larval mortality of *C. cephalonica* and further observed emergence of more males compared to females. Narangoda and Karunaratne (2009) reported that methanolic extracts of leaf and seed of *A. indica* and seed extract of *Piper nigrum* L. gave 100.0 % larval mortality of *C. cephalonica*. Further, maximum oviposition deterrence was observed with *P. nigrum* followed by *A. indica* and there is no adverse effect on the viability of maize seed.

Khani et al. (2012a) reported that petroleum ether extract of *P. nigrum* and *Jatropha curcas* L. at concentrations of 2–10 µl/g showed strong inhibition on egg hatchability and adult emergence of *C. cephalonica* with LC₅₀ values of 12.52 and 13.22 µL/mL, respectively. Zambare et al. (2012) reported that chloroform extract of *Argemone mexicana* L. at 4 ml concentration inhibited 60.02 % egg hatching of *C. cephalonica*. Fouad et al. (2014) reported that extracts of *Tithonia diversifolia* Hemsl. at 1 % w/w discouraged egg laying and larval mortality of *S. cerealella*; potentiality of this plant extract is due to the presence of sesquiterpenes, lactones (Ambrosio et al. 2008). In another recent work, Ileke (2014) reported that powders and extracts of *Capsicum frutescens* L., *Cymbopogon citratus* DC. Stapf., *Moringa oleifera* Lamm. and *Anacardium occidentale* L. at the rate of 1, 2 and 3 % concentration prevented egg hatching of *S. cerealella*.

C. Application of different botanicals in storage containers

In India, maize is generally stored in traditional storage structures such as metal bins, gunny bags, earthen bins, bamboo bins and jute bags. However, there is insignificant protection of produce from storage pests when tested for natural

infestation in local storage containers. It is recommended to treat maize with certain botanicals before storing in such containers which are found effective and sustainable. Plant materials can be used only for small scale storage for protection of stored grain. Leaves of botanicals are added in layers/dried and grind into powder/ burnt into ash/ and mixed with grain (Crop Protection Compendium 2013). Dried leaves protect the stored grain for 2 to 4 months against insect attack without any adverse effects. Hill farmers of Uttarakhand incorporate dried leaves (harvested and dried in shade for 2 days) of *Juglans regia* Linn. and *Zanthoxylum alatum* Roxb. trees for storing grain and the bitter smell of the leaves protect the produce from storage pests. Packing materials like jute bags are dipped in 10 % neem kernel solution for 15 min. After drying, grains can be stored in jute bags and the insects will be repelled by the action of botanical and the residual action will persist for 4 months. Small pieces of rhizomes of *A. calamus* were mixed with maize grains stored in bamboo baskets for the control of weevil. Grain can also be stored effectively in bamboo bins painted with a solution prepared from neem cake.

Chikukura et al. (2011) evaluated leaf powders of *Lippia javanica* Burm.f. and wood of *Spirostachys africana* Sond. at concentrations of 2 and 5 % w/w against storage insects by keeping the treated grains in polypropylene bags and then stored in improved brick and grass thatched smallholder granaries. The result of the experiment showed that *L. javanica* proved to be the best in reducing the grain damage caused by storage pests. Duruigbo (2010) reported that neem seed powder, pepper fruit seed powder protected the maize seed from damage by storage insects when stored in airtight plastic containers without affecting the seed viability. Iliyasu and Gabriella (2015) applied paste of repellent plant materials between the layers of double bagged grain. The result indicated that combination of *Cymbopogon nardus* L. and *Ocimum basilicum* L. at 0.5 % w/w was significantly more effective in repelling *T. castaneum* adults.

In our laboratory we have been working on botanicals for the integrated management of storage insects of maize from the last 5 years. The leaf powders of *Vitex negundo* L., *Adathoda vasica* L., *Catharanthus roseus* L. and *L. camara* at 5 % w/w were evaluated against *S. oryzae* in stored maize. All the treatments proved to be very toxic towards *S. oryzae* adults (Lakshmi Soujanya et al. 2012a). In our earlier research, application of acetonic extracts of *V. negundo*, *A. vasica*, *C. roseus* at 1 and 2 % concentration induced contact toxicity to *S. cerealella* resulting in suppression of adult emergence, grain damage and grain weight loss in stored maize (Lakshmi Soujanya et al. 2012b). The acetone extracts of *A. vasica*, *L. camara* and *V. negundo* at 1 and 2 % w/v had contact and repellent effect against *S. oryzae* without affecting germination. (Lakshmi Soujanya et al. 2013b). Also, the effectiveness of three medicinal plants *Cissus quadrangularis* L., *Albizia lebbek* L. and *Ageratum conyzoides* L. along with

Table 2 Structures of bioactive compounds isolated from some of the botanicals

S.No	Plant species	Bioactive compound	Chemical Structures
1.	<i>Bobgunnia madagascariensis</i> Desv. J.H. Kirkbr & Wiersema	Quercetin	
2.	<i>Ruta chalepensis</i> L.	Quinoline	
3.	<i>R. chalepensis</i>	Quinolene-4-carbaldehyde	
4.	<i>R. chalepensis</i>	Quinolene-3-carbldehyde	
5.	<i>Derris scandens</i> Benth.	Osajin	
6.	<i>D. scandens</i>	Lupaligenin	
7.	<i>D. scandens</i>	Scandinone	
8.	<i>D. scandens</i>	Sphaerobioside	
9.	<i>D. scandens</i>	Genistein	
10.	<i>D. scandens</i>	Prenylated isoflavones	
11.	<i>Peltophorum pterocarpum</i> DC. Heyne.	Sitosterol beta d glucopyranoside	
12.	<i>Thujopsis dolabrata</i> L.	Carvacrol	
13.	<i>Illicium difengpi</i> BN Chang	Safrrole	
14.	<i>I. difengpi</i>	Linalool	
15.	<i>Aframomum melegueta</i> K. Schum	R-Linalool	
16.	<i>A. melegueta</i>	2-heptanol	
17.	<i>Alpinia conchigera</i> Griff.	4-terpenenol	
18.	<i>Laurus nobilis</i> L.	1,8- Cineole	
19.	<i>L. nobilis</i>	Isovaldehyde	
20.	<i>Allium sativum</i> L.	Diallyldisulphide	
21.	<i>A. sativum</i>	Diallyltrisulphide	
22.	<i>Foeniculum vulgare</i> Mill.	Estragole	
23.	<i>Carum carvi</i> L.	Carvone	
24.	<i>Artemisia annua</i> L.	Thujone	
25.	<i>Lavandula angustifolia</i> Mill.	Limonene	

three storage regimes (Aluminium foil bag, Jute bag and cloth bag) were tested against *S. oryzae*. The results revealed that maize treated with *A. conyzoides* @ 2 % w/w stored in jute bags indicated highest mortality of *S. oryzae*, led to minimum grain weight loss and depressed progeny development at 40 and 80 days after introduction of weevils (Lakshmi Soujanya et al. 2013c). Additionally, we evaluated the effectiveness of *A. conyzoides* leaf powder at 5 % w/w in combination with hermetic storage (by storing maize in high density and double layered polythene bags). The results revealed that the number of offsprings of *S. oryzae* and *S. cerealella* emerged from treated maize stored in high density polythene bags were considerably lower (Lakshmi Soujanya et al. 2014). In our current study, dichloromethane extracts of *Ixora coccinea* L. and its pure isolated compound, tanacetene (2,6,11-trimethyl-dodeca-2,6,10-triene) proved to be superior with regard to adult mortality against *S. oryzae* in stored maize (un published data). The structure of isolated compound and its toxicity was shown in Fig. 1. Many researchers have worked on different botanicals for the control of storage insect pests. In India still, there is wide range of botanicals to be exploited particularly medicinal plants for the development of potent novel molecules as they are mostly safe to non target organisms.

Effect of plant essential oils on storage pests of maize

Essential oils are complex mixtures of 20–60 organic compounds such as monoterpenes, phenols and sesquiterpenes abundantly found in some families such as Rutaceae, Umbeliferae, Myrtaceae, Labiateae; act synergistically within the plant (Feng and Isman 1995); give characteristic odour and flavour to leaves, flowers, fruits, seed, bark and rhizomes (Bakkali et al. 2008). Especially, the monoterpenes are recently emerged as most effective compounds responsible for fumigant activity, insecticidal, antifeedant, repellents and growth regulatory activities against storage pests (Regnault-Roger and Hamroui 1995; Koul et al. 2008; Yao et al. 2008). Mint, thyme, rosemary, clove, lemon grass, cinnamon, oregano and basil are the plants containing potent essential oils. Resistance development in insects can be reduced by the use of essential oils due to synergistic action between different molecules of the oil (Varma and Dubey 1999).

A. Bioactivity of plant essential oils on adults

Bekele et al. (1996) tested essential oil extract of *Ocimum suave* Willd at higher doses against storage insects of maize and found 100.0 % mortality of *S. cerealella* and *R. dominica*. Moreover, the tested plant materials were highly repellent to *S. zeamais* and provided good protection. Carvacrol (12) isolated from *Thujopsis dolabrata* Asuhi exhibited insecticidal and fumigant action against *S. oryzae* (Ahn et al. 1998). In general,

eggs are the most resistant ones while adults are most susceptible to fumigant toxicity (Wang et al. 2006). 1,8-cineole (14), one of the components of the essential oil of *Artemisia annua* L. at 4 µl/ml of acetone have been reported to possess repellent and insecticidal effects against *S. oryzae* (Aggarwal et al. 2001).

Kim et al. (2003) screened five essential oils for their insecticidal activities and found potent insecticidal activity against adults of *S. oryzae* by *Cinnamomum cassia* Nees., *Cochlearia armoracia* L. and *Brassica juncea* L. oils at 3.5 mg/cm², within 1 day after treatment. Safrole (13) isolated from essential oil of *Laurelia sempervirens* (Ruiz & Pavon) Tul. exhibited insecticidal activity against *S. zeamais*, *T. castaneum* (Huang et al. 1999) and *S. oryzae* (Kim and Park 2008). Tripathi and Upadhyay (2009) reported repellent and insecticidal activities of leaf essential oil of *Hyptis suaveolens* L. against *S. oryzae* and *T. castaneum*. Zapata and Smagghe (2010) reported contact (39 to 44 µg/cm²), repellent (0.032 µl/cm²) and fumigant toxicities (1.6 to 1.7 µl/l) with different ranges of essential oils extracted from the leaves and bark of *L. sempervirens* against *Tribolium castaneum*.

Safrole, essential oil constituents isolated from stem bark of *Illicium difengpi* B N Chang showed pronounced contact toxicity against *S. zeamais* (LD₅₀ -8.54 µg/adult) and *T. castaneum* (LD₅₀-4.67 µg/adult). Further it was reported that linalool (14) possessed strong fumigant toxicity against both insect pests (LC₅₀=10.02 mg/L for *S. zeamais*; 9.34 mg/L for *T. castaneum*) (Chu et al. 2011). In Calabar, Nigeria, monoterpenoids (*R*)-linalool (15) and 2-heptanol (16) isolated from essential oils of *A. melegueta* and *Zingiber officinale* Roscoe were found to be repellent against *T. castaneum* and *R. dominica* (Ukeh and Umoetok 2011). Suthisut et al. (2011) demonstrated fumigant toxicity of essential oils from rhizomes of *Alpinia conchigera* Griff. and pure compound Terpinen-4-ol (17) against *S. zeamais* and *T. castaneum*. Jemaa et al. (2012) noted that essential oils from leaves of *Laurus nobilis* L. were repellent and fumigant at 0.12 µl/cm² to adults of *R. dominica* and *T. castaneum*. Further 1,8-cineole (18), linalool and isovaleraldehyde (19) were identified as major compounds responsible for insecticidal activity in tests with essential oils against *T. castaneum*. Diallyl disulphide (20) and diallyl trisulphide (21), essential oil components of garlic exhibited fumigant activity, behavioural deterrent and ovipositional inhibitor against *S. cerealella* (Yang et al. 2012) and also highly toxic to *S. zeamais* and *T. castaneum* (Huang et al. 2000).

Similarly, UshaRani (2012) showed contact toxicity and fumigant activity at 130 µg/cm² with essential oils of *Pinus longifolia* L., *Eucalyptus obliqua* L., *Coriandrum sativum* L. against *S. oryzae* and *C. cephalonica*. Essential oil derieved from *Eucalyptus astringens* Maiden exhibited repellent action at 0.08 µl/m², (58.75 %) against *R. dominica* after 24 h of exposure (Khemira et al. 2012) whereas Khani et al. (2012b) observed highest toxicities of *S. oryzae* adults with essential oils of *Mentha piperita* L. and *P. nigrum* with LC₅₀ values of

S. oryzae, Waterford et al. (2004) observed enhanced toxicity of the (95:5 % v/v) mixture containing carvone (23) or thujone (24) at 24 h exposure. DaCosta et al. (2006) studied the fumigant toxicity of mustard essential oil against first, third-instar larvae and pupa of *S. zeamais*. The LC_{50} and LC_{95} against first and third-instar larvae and pupa were found to be 4.63 and 10.32; 5.17 and 13.29; and 6.17 and 15.78 ml/L jar volume, respectively. Further, it was reported first instar larvae of *S. zeamais* were more susceptible than third-instar while pupal stage was most resistant to the vapors of mustard essential oil. Islam et al. (2009) demonstrated fumigant toxicity at dosage of 12.0 µg/mL, contact toxicity at 20 µg/mL and repellent activities at 12 µg/mL with essential oil of *Coriandrum sativum* L. against eggs, larvae and adults of *T. castaneum*. In spite of advantages from essential oils, much research should be focussed on affect of seed germination, nutritional quality of treated seed, tainting and residues in essential oil treated produce before going for recommendation.

Effect of Nano based botanical derivatives on storage pests

Nano technology is the most promising recent approach and can be used as an innovative tool for the control of storage insects. In nano formulations active compound concentrates near the center core, lined by the matrix polymer and is slowly but efficiently released to a particular host which can overcome the constraints of plant essential oils. Nano formulations increase the solubility of active ingredient and protect it from premature degradation which leads to more effective interaction with target insect. Further, it was reported that micro encapsulation reduces the loss of active principles leading to high loaded micro particles that offers the possibility of controlled drug release and phytotoxicity of essential oils can be reduced. Nanospheres, nanocapsules and nanogels are the most popular shape of nano materials used in controlled release formulations. For example in the preparation of nano material in capsule form, garlic essential oil is an active compound and polyethylene glycol acted as polymer. However, very little research has been done on the application of nano materials specifically on storage insect pests.

Yang et al. (2009) reported that nanoparticles loaded with garlic essential oil is most effective against *Tribolium castaneum* Herbst. Stadler et al. (2010) showed that nano alumina has potential to control stored grain insects. Nano ingredients of nanotube have the ability to stick to the surface hair of insect pests and ultimately enters the body and influences certain physiological functions (Patil 2009). Negahban et al. (2012) studied the effect of nano-capsules of essential oil from *Cuminum cyminum* L. which was prepared by in situ

polymerization (O/W) emulsion using poly urea-formaldehyde and reported that the fumigant toxicity from nanocapsules (LC_{50} = 16.25 ppm) were highly effective compared to pure essential oil (LC_{50} = 32.12 ppm) after 7 days of exposure. Zahir et al. (2012) synthesized silver nano particles by using extracts of *Euphorbia prostrata* L. and determined its insecticidal activity against *S. oryzae*. Complete mortality (100 %) of *S. oryzae* adults was observed on 7th day at 250 mg/kg seed and indicated the potentiality for development as botanical based nano particles. Vani and Brindhaa (2013) reported that amorphous silica nano particles were found to be highly effective against *C. cephalonica* causing 100 % mortality. Gonzalez et al. (2014) reported that nano particles increased the residual contact toxicity of *T. castaneum* and *R. dominica* due to slow and persistent release of active terpenes isolated from *Geranium* and Bergamot. A recent investigation by Ziaee et al. (2014) demonstrated fumigant toxicity of *C. cyminum* oil loaded nano gels (OLNs) against *S. granarius* and *T. castaneum* and revealed OLN were most toxic and encapsulation improved the persistence of the oil. Detailed investigation should be focused on the development of new formulations based on products derived from plants as well as the use of nanotechnology which will improve the stability and potentiality of natural products. Besides, detailed studies are also essential on the biosafety of nano particles to other non target organisms.

Mode of action

Understanding the mode of action of botanicals is important to delay the development of insecticide resistance in target insect pests. Several authors have worked on mode of action of botanicals against storage insect pests (Talukder et al. 2004; Copping and Duke 2007; Rattan 2010). The bioactivity, mammalian toxicity Oral (rat) LD 50 (mg/kg) and mechanisms of action of different botanicals effective against storage pests were shown in Tables 3 and 4. Plant extracts and essential oils are highly lipophilic and have the ability to penetrate through insect cuticle (Tripathi et al. 2009). In particular to neem, azadirachtin (active ingredient) causes sterilization of insect pests, disrupting moulting of larvae, nymphs, mating and sexual communication, inhibiting the formation of chitin, impaired fitness and reproductive activity, modifies insect development by inhibiting the release of prothoracicotropic hormones and allatotropins (Banken and Stark 1997) however, it lacks contact toxicity (Islam and Talukder 2005; Morgan 2009); rotenone is powerful inhibitor of cellular respiration, exerts its toxic effect on nerve and muscle cells; pyrethrins block voltage gated sodium channels in nerve axon; essential oils monoterpenes are inhibitors of choline esterase (Miyazawa et al. 1997; Owokotomo et al. 2015) while some plant derivatives inhibit moulting processes resulting in

Table 3 Bioactivity and mammalian toxicity of botanicals effective against storage insects

Name of the plant	Bioactivity	Mammalian toxicity Oral (rat) LD 50 (mg/kg)
<i>Acorus calamus</i> L.	Antigonadial activity	200–500
<i>Allium sativum</i> L.	Insecticidal	4800
<i>Annona squamosa</i> Linn.	Insecticidal	300
<i>Azadirachta indica</i> A. Juss.	Antifeedant, insect growth regulator, repellent	>5000
<i>Aloe vera</i> L.	Repellent	>200
<i>Carum carvi</i> L.	Fumigant	1640
<i>Chrysanthemum cinerariifolium</i> Trevir.	Insecticidal	350–500
<i>Derris elliptica</i> Wall.	Insecticidal	132
<i>Euphorbia fischeriana</i> Steud.	Feeding deterrent	>1500
<i>Eucalyptus globulus</i> Labill.	Repellent	12,302
<i>Eucalyptus saligna</i> Sm.	Insecticidal and repellent	2290
<i>Nicotiana tabacum</i> L.	Insecticidal	50–60
<i>Ocimum gratissimum</i> L.	Insecticidal, repellent	>12,882
<i>Pongamia pinnata</i> L.	Repellent, antifeedant	2000
<i>Ricinus communis</i> L.	Insecticidal	2000
<i>Schoenocaulon officinale</i> Schltdl. & Cham.	Neurotoxic	4000
<i>Tagetes erecta</i> L.	Repellent	3700
<i>Vitex negundo</i> L.	Repellent, fumigant	2000

considerable reduction of insect population (Mohal et al. 2006); interfere with normal growth processes (Dwivedi and Garg 2003; Morya et al. 2010).

N- β -glucopyranosyl-p-hydroxy phenyl acetamide, p-hydroxy phenyl acetic acid and p-hydroxyphenyl acetonitrile isolated from *Drypetus gossweileri* Exell. inhibit the activity of acetylcholinesterase (Fournier 2005; Dohi et al. 2009) of insect pests where as terpenoid limonene (25) increases the spontaneous activity of sensory nerves. Chaubey (2011) reported that inhibition of AChE activity occurred by fumigation of *S. oryzae* adults with sublethal concentrations of α -pinene, β -caryophyllene isolated from essential oils of *C. cyminum* and *P. nigrum* whereas Miyazawa et al. (2001) and Houghton et al. (2006) observed inhibition of acetylcholine esterase activity by terpenes. Methyl isothiocyanate isolated from *Boscia senegalensis* Lam Ex. Poir. exhibited insecticidal activity against *S. zeamais* and *T. castaneum* by enzymatical

degradation of glucocapparin (Gueye et al. 2011, 2013). In recent work, Rajashekar et al. (2014b) reported coumarin, a biofumigant isolated from *L. camara* as acetylcholine esterase inhibitor of *S. oryzae*.

Constraints in the development and use of plant derived insecticides

Plant based insecticides face number of challenges in their development, manufacture and application. In India so far, only Azadirachtin (neem based), *Pyrethrum* sp, *Cymbopogon* sp are registered as botanical pesticides under Insecticides act, 1968 and among them, only neem based products hold potential (Kandpal 2014). Production of plant materials on large scale, inadequate field based data, slow action, lack of residual action, improper standardization of

Table 4 Mechanism of action of different botanical insecticides against storage insects

Botanical pesticides	Mechanism of action	References
Azadirachtin	Hormonal balance disruption	Copping and Menn (2000)
Nicotine	Mimics acetyl choline	Kukel and Jennings (1994)
Rotenone	Mitochondrial poison	Khambay et al. (2003)
Sabadilla	Affect nerve cell membrane action	Bloomquist (2003)
Thymol	GABA gated chloride channel	Enan (2005)
Essential oils	Octopaminergic system	Keane and Ryan (1999)

formulation procedures for regulatory approval, difficulty in commercialization due to high cost of meeting the registration protocols including toxicological testing and inadequate shelf life are the major problems hindering the development of plant based products.

How to overcome the constraints of botanicals

Policy makers should emphasize on propagation of plants having insecticidal properties locally on large scale so that raw materials may be available freely for production of botanical pesticides. Scientific community must produce adequate data on field based application of botanicals compared to laboratory bioassays. The shelf life of plant based pesticides can be increased by the use of nano particles like nano silica and nano alumina against storage insects. The efficacy of botanicals can also be improved by blending with fixed seed oils; for example, natural pyrethrum extract can be enhanced by blending with seed oil of *Gossypium hirsutum* (Wanyika et al. 2009). Residual action can be enhanced by nano encapsulated formulations as they have the ability of control release of molecules at the site of action (Jhones et al. 2014). Formulations of botanicals can be standardized by the use of nanotechnology for isolation, purification and compounding of natural products. The cost of testing the botanical pesticides for human toxicity should be reduced so that commercialization can become easier. Use of high end technologies such as chemoinformatics, bioinformatics helps in identification of genes and pathways that are associated with secondary plant metabolites of botanicals.

Future trends

The use of plant based insecticides as synergists to synthetic insecticides have broader use in future by nano formulated bioproducts. Studies on mode of action of pure isolated compounds targeted against specific storage pests are essential. Using of biomass i.e., extraction and isolation of compounds from maize husk, silk, shank can be advantageous such as d-limonene from citrus peel (Isman 2010). Further, more biodegradable and target selective compounds are needed for integrated storage insect pest management. Investigations on mammalian toxicity and or toxicity to non target organisms, organoleptic characteristics of treated grain should be carried out apart from testing of botanicals for insecticidal, repellent and fumigant properties. As a result of nano formulations (particularly encapsulated forms) from natural plant extracts, new ways for control of storage insect pests will emerge in stored ecosystem for a secure future.

Conclusions

This review paper provides current perspective of the potentiality of botanicals for the management of storage insects of maize. Top priority must be given to insecticidal bio molecules for the control of storage insects as they are biodegradable and reduce the problem of increasing pest resistance. It is high time to focus research on use of plant derived compounds with nano particles for the development of potential stored grain protectant.

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Compliance with ethical standards

Conflicts of Interest There is no potential conflict of interest reported from the authors.

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